# A Systems Study to Determine the Attractiveness of Solar System Bodies and Sites for Eventual Human Exploration

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*Abstract*— A pre-phase A idea-generation team at the Jet Propulsion Laboratory (JPL), has conducted a study to rank all locations in the solar system based on attractiveness for human exploration. The process used to perform the study was composed of the following primary steps: determination of criteria (including value, cost, and risk criteria) upon which to rate sites in the solar system; weighting of the criteria based upon importance to eventual human exploration; selection of sites to consider and assignment of team members to the task of advocating the benefits of particular sites; rating the sites in both the short- and long-term based on team member presentations and team discussions; compilation of a score based on criteria weights and individual ratings. Finally a comparison of the total scores of different sites was completed to determine a ranking of all the bodies and sites in the solar system. Sensitivity analysis was also performed to determine how weightings affect the rankings. The criteria and methods used in this study may be valuable in determining future exploration strategies. Insight may also be gained from some potentially surprising rankings.

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## 1. INTRODUCTION

A pre-phase A idea-generation team (referred to hereafter as "Team") has been formed at JPL. This paper is the product of one of our first Team projects: categorization of sites and locations in the solar system as potential targets for human exploration. We selected this project for several reasons: 1) it gave the Team an opportunity to consider a high-level issue that provided significant learning opportunities for the Team, 2) it allowed the Team the opportunity to develop methodologies for making decisions, and 3) the products of this study may offer insight into priorities of NASA's Exploration Plan. Our belief upon the completion of this study is that the greatest benefit of this study and paper may be in the methods that we developed and used and the criteria upon which we conducted the ratings. Final rankings are subject to the knowledge base and biases of individual Team members. Some of the rankings surprised us and are presented not as conclusions but as "findings" requiring further investigation.

## 2. TEAM COMPOSITION

The charter of the Team is to be a nexus for new technology, approaches and techniques for space exploration. We strive to do three things:

1. **Develop** highly innovative and forward-looking mission architectures, technology roadmaps, and evaluation tools in support of NASA's medium-term exploration and deep space science initiatives.
2. **Provide** a low risk environment for systems leadership development and utilize evolving collaborative design processes, methods, and tools.**Achieve** continuously improved innovation.

The Team is composed of members who have deliberately diverse backgrounds. Our diversity can be viewed as a benefit or a drawback in a study like this. Some members of the Team come from a top-level systems engineering background while others have more focused technical backgrounds. Expertise and short biographies are included in **Table 1** for each Team member who participated in the study.

## 3. METHOD

After the formation of the Team and some initial meetings on developing our overall Team process, we decided to conduct a study as a test of our process and to develop Team knowledge base. We considered a variety of potential studies before selecting a ranking of all the sites in the solar system for eventual human exploration as our first Team project. "Sites" in this case includes all planets and moons as well as other prospective bodies and locations in the solar

**Table 1.** Team Eureka Members

| Team Member | Expertise | Experience |
|---|---|---|
| **Jason Andringa** | Systems engineering and pre-phase A mission architectures | Jason Andringa has been with JPL for three and a half years. He develops pre-phase A mission architectures and focuses on human precursor missions to Mars. Mr. Andringa has participated in several proposal efforts in roles such as cost engineering, systems engineering, and proposal management. He has also been a member of JPL's concurrent engineering Team X. Mr. Andringa is working toward an MBA at USC and has an MS from MIT in Aeronautics/Astronautics and a BS from Calvin College in Mechanical Engineering. |
| **Payman Arabshahi** | Adaptive and intelligent systems, digital signal processing and digital communications. | Payman Arabshahi obtained his M.S. and PhD in Electrical Engineering from the University of Washington in 1990 and 1994 respectively. He has served on the faculties of the University of Alabama in Huntsville and University of Washington. Since 1997 he has been on the technical staff of the Jet Propulsion Laboratory. He holds three NASA Tech Briefs and is currently leading tasks on swarm intelligence approaches to network communications. He is also a co-PI on a project dealing with development of wireless nodes for an ad hoc, multi-hop wireless network. Payman is also on the faculty of the Electrical Engineering Department at Caltech, where he teaches the 3-course graduate sequence on digital communications. He has been a guest editor of the IEEE Transactions on Neural Networks; and was an invited special session chair and organizer for the IEEE World Congress on Computational Intelligence, May 2002, and served on the technical program committee of the 2002 IEEE CAS Workshop on Wireless Communications and Networking. He is the co-chair of the 2005 IEEE Swarm Intelligence Symposium |
| **Andrew Gray** | Communications architectures, systems, and advanced prototypes | Andrew Gray has been with JPL for six years and is currently a group supervisor in the Communications Architectures and Research Section. He leads first-of-a-kind communication prototype developments, and performs communications system design and analysis. Mr. Gray also leads research tasks in the areas of signal processing and intelligent systems and works with cross-disciplinary teams in the development of Space Mission Concepts and Architectures. Previously Mr. Gray worked in the Microelectronics and Signal Processing Branch at NASA's Goddard Space Flight Center. He earned a MBA and PhD in electrical engineering from the University of Southern California in 2004 and 2000, respectively; he earned a MS in electrical engineering from the Johns Hopkins University in 1997 and a BS in electronics engineering with a minor in mathematics from Pittsburg State University in 1994. |
| **Jennifer Law** | Planetary protection, medicine, space human factors | Jennifer Law has been a planetary protection engineer at JPL since 2001. She currently works part-time on advanced studies while she attends medical school at the University of Southern California. She worked on the Mars Exploration Rover project from 2001-2003 and served as planetary protection lead for two Scout proposals in 2002. Previously, she supported space human factors research at Ames Research Center and MIT's Man Vehicle Laboratory. She earned an SB in electrical engineering with minors in biomedical engineering and psychology from MIT in 2001. |
| **Arbi Karapetian** | Spacecraft systems engineering and operations | Arbi Karapetian has been with JPL since August of 2000 and is currently a systems engineer on the Cassini Project. He also works with cross-disciplinary teams in the development of space mission concepts and architectures. Previously at JPL, Mr. Karapetian has performed radiation modeling for COTS-based space computers. He has served as flight director for Hughes space and communications earth orbiting missions as well as worked in development of mission architecture concepts for such missions. He earned his MS in Spacecraft System Architecture and Engineering from University of Southern California in 2004, and his BS in Solid State Physics from University of California at Los Angeles in 1995. |
| **Elisabeth Lamassoure** | Systems engineering and pre-phase A mission architectures | Elisabeth Lamassoure has been at JPL since October 2001 as a System Engineer in the Mission & Systems Architecture Section (311) and is now Lead System Chair in the Advanced Project Design Team (Team X). She is completing an R&TD task in the area of model-based engineering for pre-Phase A trade space exploration. In the past, she participated as a System Engineer in advanced studies for the Mars Exploration Program, Inner and Outer Planets Exploration Program, as well as in proposal efforts for the Mars Scout and New Frontiers Program, and numerous Team X Studies.<br>Elisabeth received a general science and engineering degree from Ecole Polytechnique, France, in 1999 (MS-level), and a MS in Astronautics from the Massachusetts Institute of Technology in 2001. |
| **Greg Mungas** | Systems engineering, space-based instrument systems, and micro-spacecraft technologies | Greg Mungas recently joined JPL to work in JPLÕs Mars mission architecture group based in section 312 (formerly 311). His area of focus in the various advanced systems studies for the Mars Program Office is centered around instrumentation, payload, ~~and science~~ measurement goals for a variety of upcoming missions (Human Precursor, Astrobiology Field Lab, MSL derivatives, and next decade Mars missions). GregÕs technical work with instrumentation includes: proposal manager on an MSL flight proposal and institutional principal investigator on three NASA instrument awards (a PIDDP (Planetary Instrument Definition and Development) instrument nearing completion, and two ASTID (Astrobiology Instrument Development) instruments that have been recently awarded.) Greg also was recently involved as a proposal manager outside of JPL for a Mars Scout mission (HOMER). |
| **Max Vozoff** | RF communications, radiometric hardware, aerospace systems, mission design | Max Vozoff has been a Senior Engineer at JPL for 5 years and has been involved in hardware design and testing for numerous flight missions and technology developments, including COSMIC, GRACE, AFF (ST3, TPF) & CCNT (ST5). He has also led and participated in numerous advanced mission studies using micro-systems and state-of-the-art technologies. Prior to joining JPL he spent seven years working for commercial communications companies as an RF hardware engineer. He earned a BEE Honors (Communications) from Curtin University in Western Australia in 1993 and a MS (Astronautics) from USC in 2003. |
| **John Ziemer** | Propulsion, micropropulsion, and microspacecraft | John Ziemer has been working at JPL for four years in the Advanced Propulsion Technology Group. He is the technical lead and manager of the microthruster technology development program for the Laser Interferometer Space Antenna (LISA) mission and has recently worked on the ST7-DRS project testing colloid micro-newton thrusters. To date Dr. Ziemer has participated in testing and developing over ten different microthruster concept and breadboard designs. He also works with cross-disciplinary teams in the development of space mission concepts and architectures and has been an advisor to many students during summer programs at JPL. Dr. Ziemer earned his MA and PhD in Mechanical and Aerospace Engineering and Plasma Science and Technology from Princeton University in 1997 and 2001, respectively. He earned his BS in Aerospace Engineering from the University of Michigan in 1994. |

system such as asteroids, comets, Lagrange points, and open space. One of the hallmarks of the Team is that leadership is fluid. Although Andrew Gray is the leader of the Team, leadership is intentionally passed to the person on the Team most qualified or desirous of leadership in any particular study. Jason Andringa (author) took on the leadership responsibilities of this study. Jason was a logical choice to act as leader in this study because he suggested the concept for the study and has significant experience in human mission architectures.

After selecting the concept we would study, our first task was to determine the criteria upon which we would rank all the sites in the solar system. Suggestions were solicited and the final list of rankings was finalized during a Team meeting. We developed criteria under three broad categories: value, cost, and risk criteria. Our final list of criteria is presented in **Table 2**. Table 2 also provides the initial weightings that were applied to each criterion. The author set the initial weightings based on his own understanding of the importance of different criteria. Weightings are based on a scale of 1 to 10 with 10 being the most important. Rather than attempt to come to Team consensus on the weightings of the criteria, the Team decided that doing sensitivity analysis to the weightings after voting was complete was more valuable than attempting to arrive at Team consensus on the weightings. Sensitivity analysis in this case involves changing values of the weightings to see how ranking outcomes are affected. Some of the significant results of this analysis are presented in the

**Table 2.** Criteria and Initial Weightings

| CRITERIA | | Weights (0-10 with 10 being most important) |
|---|---|---|
| | **Value-related** | |
| | General scientific interest | 9 |
| | Likelihood of finding life | 7 |
| | Scientific value of *human* presence at that location versus robots | 9 |
| | Entertainment / Public outreach interest in having *human* presence at that location (reality shows?) | 5 |
| | Local resources available to use in situ | 6 |
| | Local resources available to use back at Earth | 5 |
| | Potential for in situ manufacturing to benefit humans on Earth | 4 |
| | Attractiveness for eventual human colonization | 10 |
| | Tourism interest of the location | 5 |
| | National "prestige" gained by exploring the location | 4 |
| | Benefits to national defense | 1 |
| | Benefits to planetary defense (i.e. defense from Earth-crossing asteroids) | 7 |
| | Useful as a "stepping stone" to other sites in the solar system | 3 |
| | Proximity to other valuable sites in the solar system | 2 |
| | Value for astronomical observations | 6 |
| | **Cost-related** | |
| | Time to reach (with reasonable delta-V) and come back --as it relates to cost | 8 |
| | Difficulty of landing (or orbit insertion) and coming back -- as it translates into mass | 6 |
| | Survivability based on the environment at that location (making Venus difficult and Mercury challenging...) | 9 |
| | Ease of using local resources for energy, air, food, fuel (lots of available resources may lower cost) | 6 |
| | Challenge of (scientific) payload as it relates to cost (e.g. Europa submarine) | 4 |
| | Difficulty of communications with Earth as it relates to cost | 7 |
| | Development of power sources required | 3 |
| | Extra resources required per person for survival (i.e. additional radiation shielding) | 4 |
| | **Risk-related** | |
| | Time to return to Earth (with minimal delta-V) | 8 |
| | Difficulty in the engineering challenge of keeping people alive | 7 |
| | Difficulty of communications with Earth as it relates to risk | 6 |
| | Human environmental safety | 9 |
| | Human psychological safety | 2 |
| | Human engineering safety | 5 |
| | Programmatic / political risks | 2 |
| | Abundance and variety of resources useful in emergency situations | 6 |

Findings section below.

In selecting sites in the solar system, we wanted to cover all potential sites in a logical way without actually having to discuss each moon, for instance, separately. During a Team meeting, we composed the following list of sites or groupings of sites to consider (listed in order of proximity to the Earth):

- Moon
- Venus
- Mars
- Moons of Mars
- Mercury
- Earth-crossing asteroids
- Non earth-crossing asteroids and comets
- Large gaseous planets
- Moons of gaseous planets
- Pluto
- Bodies beyond Pluto
- Lagrange points and open space

After grouping all the sites as presented above, Team members picked one or two of the sites or groupings to advocate. Some Team members selected a site or grouping based on personal knowledge in that area while others picked a site or grouping because of a desire to learn more about that site or grouping.

During the course of the next month, Team members researched their selected site or grouping as a potential location for eventual human exploration. Team members were asked to focus on 1) general characteristics, 2) potential human habitation locations at that site, and 3) reasons for exploring or colonizing. Advocates made presentations to the Team so that every Team member was presented the same information on all the sites and groupings.

After all presentations were completed, our task was to fill in a voting spreadsheet with criteria on one axis and the sites or groupings on the other axis. **Table 3** shows the voting table before it was filled in.

The voting table was set up in such a way that each cell displayed the Team average for each cell. Each Team member's vote was captured so that comparisons could later be made. Each Team member rated each site or grouping on each criteria on a scale of 1 to 10 with 10 being the highest. As a Team, we decided that we needed to consider both the short- and far-term in casting our votes. In the short-term we assumed current technology constraints. In the short-term we attempt to answer the question: What site should be focused on for human exploration now? Or what should be the goal of the space program? For the long-term we assumed technology is advanced to a point where mass and power are no longer dramatic constraints. In the long-term we attempt to answer the question: Ultimately, what is the most valuable site in the solar system?

**Table 5.** Rankings in the Long-Term

| Rank* | Long-Term | % Drop from Site Above |
|---|---|---|
| 1 | Moon | N/A |
| 2 | Mars | 7% |
| 3 | Earth-crossing asteroids | 11% |
| 4 | Moons of Mars | 5% |
| 5 | Lagrange points/open space | 9% |
| 6 | Non Earth-crossing asteroids and comets | 1% |
| 7 | Moons of gaseous planets | 5% |
| 8 | Venus | 19% |
| 9 | Mercury | 15% |
| 10 | Pluto | 2% |
| 11 | Bodies beyond Pluto | 14% |
| 12 | Large gaseous planets | 5% |
| *Rankings using criteria weightings from Table 2 | | |

After all the voting was complete, another sheet in the spreadsheet multiplied the average votes from 1 to 10 by the weighting from 1 to 10 to get an overall score for each site for every criterion. The highest possible score for any site on any particular criteria is 100. The criteria are then summed for each site to get an overall score. Rather than include the scores for any particular run (different runs involve different weightings for the criteria), some potentially significant findings are presented in the next

**Table 3.** Voting Table

| CRITERIA | Short-Term LOCATIONS | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Moon | Venus | Mars | Moons of Mars | Mercury | Earth-crossing asteroids | Non earth-crossing asteroids and comets | Large gaseous planets | Moons of gaseous planets | Pluto | Bodies beyond Pluto | Lagrange points and open space |
| **Value-related** | | | | | | | | | | | | |
| General scientific interest | ? | ? | ? | ? | ? | ? | ? | ? | ? | ? | ? | ? |
| Likelihood of finding life | ? | ? | ? | ? | ? | ? | ? | ? | ? | ? | ? | ? |
| Scientific value of *human* presence at that location versus robots | ? | ? | ? | ? | ? | ? | ? | ? | ? | ? | ? | ? |
| Entertainment / Public outreach interest in having *human* presence at that location (reality shows?) | ? | ? | ? | ? | ? | ? | ? | ? | ? | ? | ? | ? |
| Local resources available to use in situ | ? | ? | ? | ? | ? | ? | ? | ? | ? | ? | ? | ? |
| Local resources available to use back at Earth | ? | ? | ? | ? | ? | ? | ? | ? | ? | ? | ? | ? |
| Potential for in situ manufacturing to benefit humans on Earth | ? | ? | ? | ? | ? | ? | ? | ? | ? | ? | ? | ? |
| Attractiveness for eventual human colonization | ? | ? | ? | ? | ? | ? | ? | ? | ? | ? | ? | ? |
| Tourism interest of the location | ? | ? | ? | ? | ? | ? | ? | ? | ? | ? | ? | ? |
| National "prestige" gained by exploring the location | ? | ? | ? | ? | ? | ? | ? | ? | ? | ? | ? | ? |
| Benefits to national defense | ? | ? | ? | ? | ? | ? | ? | ? | ? | ? | ? | ? |
| Benefits to planetary defense (i.e. defense from Earth-crossing asteroids) | ? | ? | ? | ? | ? | ? | ? | ? | ? | ? | ? | ? |
| Useful as a "stepping stone" to other sites in the solar system | ? | ? | ? | ? | ? | ? | ? | ? | ? | ? | ? | ? |
| Proximity to other valuable sites in the solar system | ? | ? | ? | ? | ? | ? | ? | ? | ? | ? | ? | ? |
| Value for astronomical observations | ? | ? | ? | ? | ? | ? | ? | ? | ? | ? | ? | ? |
| **Cost-related** | | | | | | | | | | | | |
| Time to reach (with reasonable delta-V) and come back --as it relates to cost | ? | ? | ? | ? | ? | ? | ? | ? | ? | ? | ? | ? |
| Difficulty of landing (or orbit insertion) and coming back -- as it translates into mass | ? | ? | ? | ? | ? | ? | ? | ? | ? | ? | ? | ? |
| Survivability based on the environment at that location (making Venus difficult and Mercury challenging...) | ? | ? | ? | ? | ? | ? | ? | ? | ? | ? | ? | ? |
| Ease of using local resources for energy, air, food, fuel (lots of available resources may lower cost) | ? | ? | ? | ? | ? | ? | ? | ? | ? | ? | ? | ? |
| Challenge of (scientific) payload as it relates to cost (e.g. Europa submarine) | ? | ? | ? | ? | ? | ? | ? | ? | ? | ? | ? | ? |
| Difficulty of communications with Earth as it relates to cost | ? | ? | ? | ? | ? | ? | ? | ? | ? | ? | ? | ? |
| Development of power sources required | ? | ? | ? | ? | ? | ? | ? | ? | ? | ? | ? | ? |
| Extra resources required per person for survival (i.e. additional radiation shielding) | ? | ? | ? | ? | ? | ? | ? | ? | ? | ? | ? | ? |
| **Risk-related** | | | | | | | | | | | | |
| Time to return to Earth (with minimal delta-V) | ? | ? | ? | ? | ? | ? | ? | ? | ? | ? | ? | ? |
| Difficulty in the engineering challenge of keeping people alive | ? | ? | ? | ? | ? | ? | ? | ? | ? | ? | ? | ? |
| Difficulty of communications with Earth as it relates to risk | ? | ? | ? | ? | ? | ? | ? | ? | ? | ? | ? | ? |
| Human environmental safety | ? | ? | ? | ? | ? | ? | ? | ? | ? | ? | ? | ? |
| Human psychological safety | ? | ? | ? | ? | ? | ? | ? | ? | ? | ? | ? | ? |
| Human engineering safety | ? | ? | ? | ? | ? | ? | ? | ? | ? | ? | ? | ? |
| Programmatic / political risks | ? | ? | ? | ? | ? | ? | ? | ? | ? | ? | ? | ? |
| Abundance and variety of resources useful in emergency situations | ? | ? | ? | ? | ? | ? | ? | ? | ? | ? | ? | ? |

| CRITERIA | Long-Term LOCATIONS | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Moon | Venus | Mars | Moons of Mars | Mercury | Earth-crossing asteroids | Non earth-crossing asteroids and comets | Large gaseous planets | Moons of gaseous planets | Pluto | Bodies beyond Pluto | Lagrange points and open space |
| **Value-related** | | | | | | | | | | | | |
| General scientific interest | ? | ? | ? | ? | ? | ? | ? | ? | ? | ? | ? | ? |
| Likelihood of finding life | ? | ? | ? | ? | ? | ? | ? | ? | ? | ? | ? | ? |
| Scientific value of *human* presence at that location versus robots | ? | ? | ? | ? | ? | ? | ? | ? | ? | ? | ? | ? |
| Entertainment / Public outreach interest in having *human* presence at that location (reality shows?) | ? | ? | ? | ? | ? | ? | ? | ? | ? | ? | ? | ? |
| Local resources available to use in situ | ? | ? | ? | ? | ? | ? | ? | ? | ? | ? | ? | ? |
| Local resources available to use back at Earth | ? | ? | ? | ? | ? | ? | ? | ? | ? | ? | ? | ? |
| Potential for in situ manufacturing to benefit humans on Earth | ? | ? | ? | ? | ? | ? | ? | ? | ? | ? | ? | ? |
| Attractiveness for eventual human colonization | ? | ? | ? | ? | ? | ? | ? | ? | ? | ? | ? | ? |
| Tourism interest of the location | ? | ? | ? | ? | ? | ? | ? | ? | ? | ? | ? | ? |
| National "prestige" gained by exploring the location | ? | ? | ? | ? | ? | ? | ? | ? | ? | ? | ? | ? |
| Benefits to national defense | ? | ? | ? | ? | ? | ? | ? | ? | ? | ? | ? | ? |
| Benefits to planetary defense (i.e. defense from Earth-crossing asteroids) | ? | ? | ? | ? | ? | ? | ? | ? | ? | ? | ? | ? |
| Useful as a "stepping stone" to other sites in the solar system | ? | ? | ? | ? | ? | ? | ? | ? | ? | ? | ? | ? |
| Proximity to other valuable sites in the solar system | ? | ? | ? | ? | ? | ? | ? | ? | ? | ? | ? | ? |
| Value for astronomical observations | ? | ? | ? | ? | ? | ? | ? | ? | ? | ? | ? | ? |
| **Cost-related** | | | | | | | | | | | | |
| Time to reach (with reasonable delta-V) and come back --as it relates to cost | ? | ? | ? | ? | ? | ? | ? | ? | ? | ? | ? | ? |
| Difficulty of landing (or orbit insertion) and coming back -- as it translates into mass | ? | ? | ? | ? | ? | ? | ? | ? | ? | ? | ? | ? |
| Survivability based on the environment at that location (making Venus difficult and Mercury challenging...) | ? | ? | ? | ? | ? | ? | ? | ? | ? | ? | ? | ? |
| Ease of using local resources for energy, air, food, fuel (lots of available resources may lower cost) | ? | ? | ? | ? | ? | ? | ? | ? | ? | ? | ? | ? |
| Challenge of (scientific) payload as it relates to cost (e.g. Europa submarine) | ? | ? | ? | ? | ? | ? | ? | ? | ? | ? | ? | ? |
| Difficulty of communications with Earth as it relates to cost | ? | ? | ? | ? | ? | ? | ? | ? | ? | ? | ? | ? |
| Development of power sources required | ? | ? | ? | ? | ? | ? | ? | ? | ? | ? | ? | ? |
| Extra resources required per person for survival (i.e. additional radiation shielding) | ? | ? | ? | ? | ? | ? | ? | ? | ? | ? | ? | ? |
| **Risk-related** | | | | | | | | | | | | |
| Time to return to Earth (with minimal delta-V) | ? | ? | ? | ? | ? | ? | ? | ? | ? | ? | ? | ? |
| Difficulty in the engineering challenge of keeping people alive | ? | ? | ? | ? | ? | ? | ? | ? | ? | ? | ? | ? |
| Difficulty of communications with Earth as it relates to risk | ? | ? | ? | ? | ? | ? | ? | ? | ? | ? | ? | ? |
| Human environmental safety | ? | ? | ? | ? | ? | ? | ? | ? | ? | ? | ? | ? |
| Human psychological safety | ? | ? | ? | ? | ? | ? | ? | ? | ? | ? | ? | ? |
| Human engineering safety | ? | ? | ? | ? | ? | ? | ? | ? | ? | ? | ? | ? |
| Programmatic / political risks | ? | ? | ? | ? | ? | ? | ? | ? | ? | ? | ? | ? |
| Abundance and variety of resources useful in emergency situations | ? | ? | ? | ? | ? | ? | ? | ? | ? | ? | ? | ? |

section.

## 4. Findings and Sensitivity Analysis

The numerical values are subject to ratings provided by the Team members involved in this study. A different Team would surely produce results with different numerical values The final rankings may prove to be similar or identical with a different Team composition, however, and are presented below. We believe the value of this study is in the criteria selected, the groupings of sites selected, and the methods used in conducting the study. Rankings may be deemed valuable or non-valuable at the reader's discretion. Using the weightings presented in Table 2, the rank order of sites in the short-term is presented in **Table 4.** Table 4 (and all subsequent tables) also shows the percent drop in score between a site and the site ranked one spot above.

**Table 5** shows the rankings in the long-term using the weightings in Table 2. The order is very similar to the order in Table 4 except that *Large gaseous planets* dropped below *Bodies of Pluto* to claim the bottom spot. The percentage drop from one site to the next is also quite different in some cases.

**Table 6** displays the rankings in the short-term with all weightings set equal to one. In this case there is no bias between criteria. The order of the sites turns out to be exactly the same as in Table 4. The changes in percentage between tables 4 and 6 provide an indication of the bias (whether justified or not) inherent in the weightings submitted by the author in Table 2.

**Table 7** shows the ranking in the long-term with all weightings set equal to one. Once again the order of sites turns out to be exactly the same as in the previous long-term table, Table 5. Differences in the percentage drop are once again an indication of the individual bias of the author in his weightings in Table 2.

It is also possible to modify the spreadsheet to look at rankings if only value-, cost-, or risk-related criteria are considered. In each of these cases, the order is very similar to the charts above with small movements in some cases. In every case, the Moon always comes in first and Mars always comes in second (if only value-related criteria are considered, Earth-crossing asteroids pulls into a tie with Mars as the second most valuable site after the Moon ). The fact that the Moon beats Mars in all cases was a significant finding in the opinion of the author. The author assumed that Mars would come in first place due to such factors as scientific interest, attractiveness of human colonization, and prestige of exploring the site. Mars does, in fact, rate first in those individual criteria, but it is beat out by the Moon in almost every other criterion. In fact, the Moon has a higher rating in every cost- and risk-related criterion. In the case where only risk-related criteria are considered, the Moon's ranking over Mars' ranking in the short- and long-term increases to 19% and 16% respectively. The finding that the Moon scores higher than Mars overall in every case considered in this study may cause NASA architects to re-think strategies that assume Mars is ultimately the most enticing site for human exploration and colonization in the solar system. Based on this study, the Moon may be the most enticing site for human exploration and colonization in the solar system rather than simply a stepping stone to other sites such as Mars.

Another finding that was somewhat surprising to the author and the Team is that the rankings changed very little between the short-term and the long-term. *Bodies of Pluto* and *Large gaseous planets* changed places at the bottom of the rankings between the short- and long-term using both the weightings in Table 2 and equal weightings. That was the only change in the rankings. The Team assumed that there would be greater differences in the relative attractiveness of different sites based on time horizon. A trend that is obvious from Tables 4-7 is that proximity to the Earth increases the attractiveness of a site. *Moons of gaseous planets* ranks disproportionably high based on value-related

**Table 4.** Rankings in the Short-Term

| Rank* | Short-Term | % Drop from Site Above |
|---|---|---|
| 1 | Moon | N/A |
| 2 | Mars | 10% |
| 3 | Earth-crossing asteroids | 15% |
| 4 | Moons of Mars | 3% |
| 5 | Lagrange points/open space | 13% |
| 6 | Non Earth-crossing asteroids and comets | 2% |
| 7 | Moons of gaseous planets | 1% |
| 8 | Venus | 21% |
| 9 | Mercury | 14% |
| 10 | Pluto | 7% |
| 11 | Large gaseous planets | 12% |
| 12 | Bodies beyond Pluto | 11% |
| *Rankings using criteria weightings from Table 2 | | |

**Table 6.** Rankings in the Short-Term

| Rank* | Short-Term | % Drop from Site Above |
|---|---|---|
| 1 | Moon | N/A |
| 2 | Mars | 15% |
| 3 | Earth-crossing asteroids | 11% |
| 4 | Moons of Mars | 5% |
| 5 | Lagrange points/open space | 8% |
| 6 | Non Earth-crossing asteroids and comets | 6% |
| 7 | Moons of gaseous planets | 5% |
| 8 | Venus | 21% |
| 9 | Mercury | 13% |
| 10 | Pluto | 7% |
| 11 | Large gaseous planets | 9% |
| 12 | Bodies beyond Pluto | 13% |
| *Rankings using all criteria weightings equal | | |

**Table 7.** Rankings in the Long-Term

| Rank* | Long-Term | % Drop from Site Above |
|---|---|---|
| 1 | Moon | N/A |
| 2 | Mars | 11% |
| 3 | Earth-crossing asteroids | 7% |
| 4 | Moons of Mars | 7% |
| 5 | Lagrange points/open space | 6% |
| 6 | Non Earth-crossing asteroids and comets | 4% |
| 7 | Moons of gaseous planets | 8% |
| 8 | Venus | 19% |
| 9 | Mercury | 13% |
| 10 | Pluto | 2% |
| 11 | Bodies beyond Pluto | 14% |
| 12 | Large gaseous planets | 2% |
| *Rankings using all criteria weightings equal | | |

criteria while *Venus* and *Mercury* rank disproportionably low due to cost- and risk-related criteria. But overall, there is a clear correlation between proximity to the Earth and ranking regardless of time horizon. This is either due to an Earth-centric bias in the Team or an understanding that travel time and distance (even when mass and power are assumed to not be constraints) are truly factors that lower attractiveness.

## 5. CONCLUSIONS

This study was an interesting and enlightening experience for the Team at JPL that conducted it. Although there were findings that surprised us and that we think may be important for NASA strategy architects to consider, we believe the value of this study lies more in the process than the results. It is difficult to quantitatively determine the attractiveness of solar system bodies and locations. This study attempted to determine attractiveness based on the compiled criteria and ratings of a Team of people who are knowledgeable in space exploration topics. The process used in this study may prove valuable in other strategic planning exercises.

## REFERENCES

[1] Numerous websites and other forms of information were consulted in developing the presentations used by advocates for different sites.

## BIOGRAPHY

**Jason Andringa** is a Staff Systems Engineer at the Jet Propulsion Laboratory. Jason worked as a Systems Engineer in JPL's innovative "Team X" concurrent engineering design environment for three years. Jason has also done work on Mars Robotic Outpost concepts and has supported several proposals in various roles including Cost Engineer, Systems Engineer, and Manager. Jason is currently developing a variety of human precursor mission concepts to Mars and is a member of JPL's "Team Eureka," an idea-generation team. Jason has a BS degree in Mechanical Engineering from Calvin College and an MS degree in Aeronautics/Astronautics from MIT. **Table X.** Summary of Style Requirements